A New "Camera on a Chip" for pRad Movies

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We have developed a camera that consists of two integrated circuits bonded together into a single "hybrid" chip. This camera can capture dynamic events in proton radiography movies with a minimum temporal resolution of 100 nanoseconds. The new camera's high light sensitivity also provides higher image quality than our current cameras. This improvement in image quality is equivalent to increasing the proton-beam intensity by a factor of 4. In addition to being able to capture multiple frames per camera, the new camera also has greater reliability, and lower cost per frame. It also takes up far less space and needs only a few external electrical connections. The new imager can also be used to study other ultrafast transient phenomena such as projectiles penetrating armor.

A proton radiography (pRad) movie records a series of images produced as protons transmitted through a dynamic experiment are focused on a scintillator screen; the scintillator material converts proton intensity to light intensity. Our current camera system allows us to capture and store a sequence of these images at rates of millions of frames per second for a fraction of a second. The system is shown in Figure 1.

At present, we make 20-to-30-frame movies at up to 2.8 million frames per second; the minimum time between frames is thus about 360 nanoseconds. To capture each frame at this rate, the camera's electronic shutter must remain open for less than 360 nanoseconds. In the future, we plan to double or triple the number of frames per movie and increase the frame rate by a factor of 5 or more, which will require shutter speeds of 60 nanoseconds or less.

However, the current system's electronic shutter—a vacuum planar photodiode—cannot operate much below 300 nanoseconds.[1] In addition,

[1] The shutter speed is limited by the power supply producing the short, 12 kilovolt pulse required to briefly open the photodiode to incident light. To a lesser extent, it is also limited by the photodiode's capacitance-limited rise time.

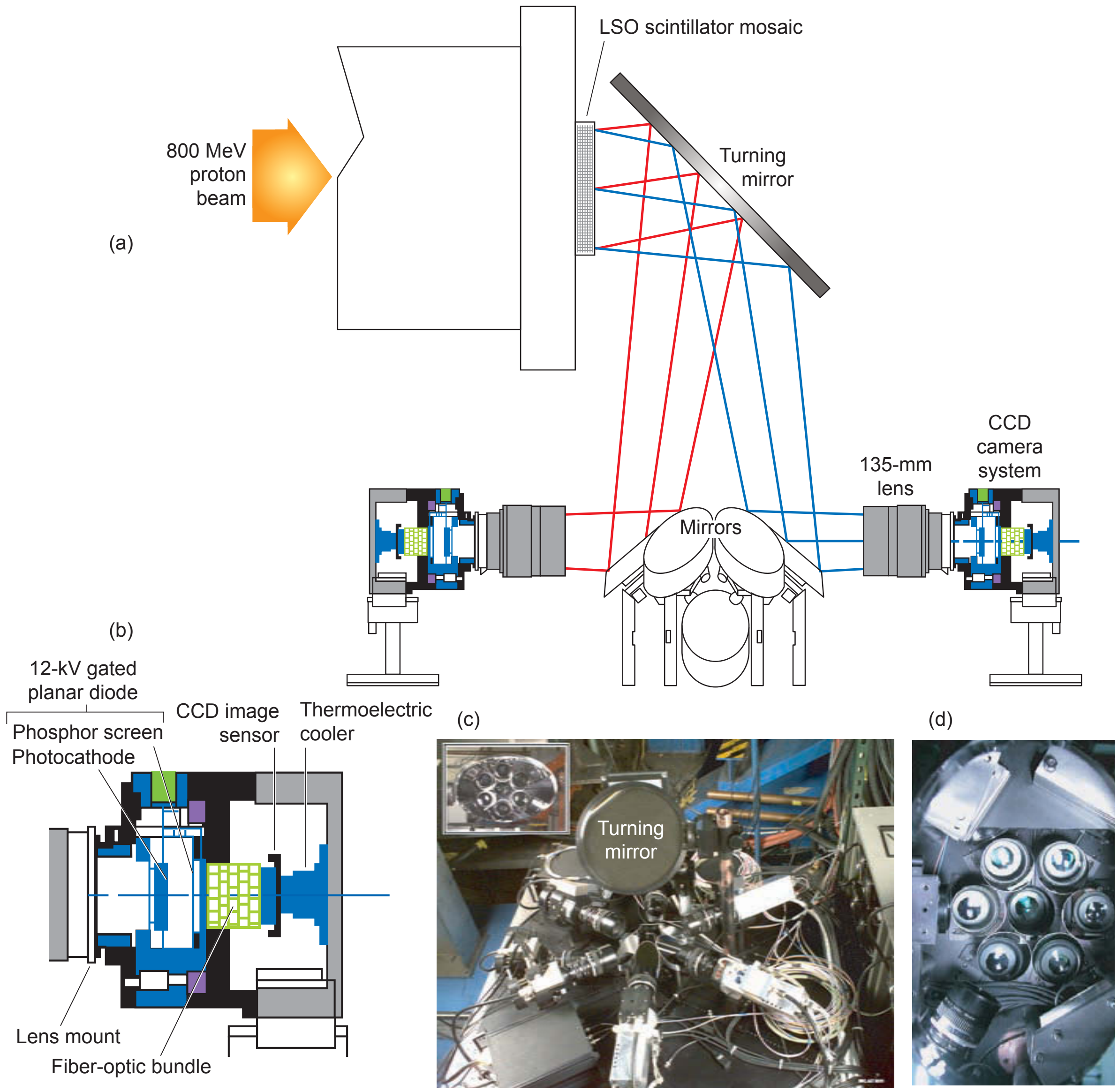


Figure 1. Proton Radiography Imaging System with Gated CCD Cameras
(a) Proton images are produced as protons transmitted through a dynamic experiment are focused on the 12-cm by 12-cm tiled LSO scintillator. The scintillator converts proton intensity to light intensity, and the “turning” mirror reflects these light images to seven smaller mirrors, which reflect the images to seven CCD cameras. (b) The gated CCD imager system consists of a CCD camera, which has no electronic shuttering capabilities, augmented by a 12-kV gated planar photodiode that acts as a fast optical shutter. A lens focuses the reflected light image onto the photodiode’s front plate, a photocathode that converts the light image to an electron image through the photoelectric effect. When the photodiode is activated by a 12-kV potential, the electrons are accelerated to the back plate, a scintillating screen that converts the electron image back to a light image. That image is transmitted through the fiberoptic bundle (to maximize light transmission) to a cooled 1600 × 1600 pixel CCD camera, which digitizes the image. The shutter speed of the photodiode is limited by the 100-ns rise and fall times for applying the 12-kV activating pulse. Although cumbersome, this shuttering method was the only high-speed electro-optic option available at the time. (c) The large gray circular object is the back of the turning mirror, beneath which are seven CCD cameras and some of the many cables and auxiliary electronics required to operate the cameras and process their outputs. Not shown is the equipment that generates the high-voltage pulses for the planar photodiodes. (d) All seven cameras are pictured from the scintillator screen’s point of view. Note the close packing of the cameras; there is little room for additional cameras. These cameras store one frame per camera—as opposed to the new camera’s three frames. Thus, the same number of new cameras will be able to capture three times the total number of frames as the old cameras. Moreover, the new hybrid cameras will reduce the total cost, real estate, and calibration time of the complete camera system.

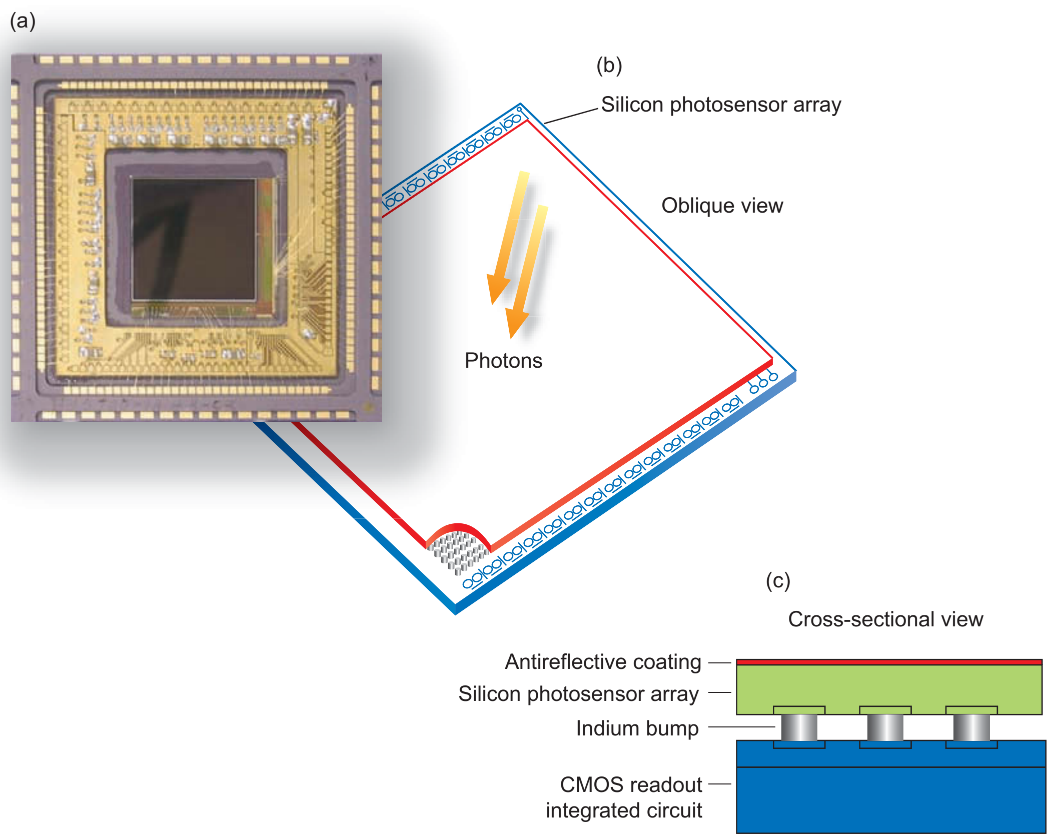


Figure 2. New High-Speed Camera on a Chip

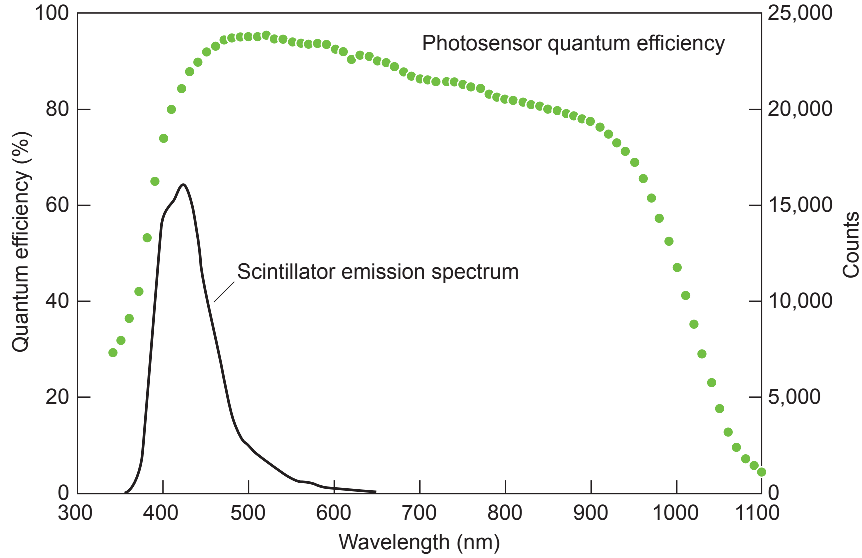
The new chip consists of a 720 × 720 pixel array of fast silicon photosensors (with 26-µm pixel pitch) bonded to a CMOS integrated circuit that turns the signals from the photosensors on and off and processes their outputs. (a) In this photo, the photosensor array is the dark rectangle. Oblique (b) and side (c) views show how the two circuits are physically and electrically connected by indium bumps, much smaller than 10 µm in diameter. The hybrid chip contains analog processing circuits, digital logic circuits, and a 12-bit analog-to-digital (A/D) converter. The only external connections required are for 2.5-, 3.3- and 14-V power supplies, clock and trigger (shutter) signals, and a digital-video output to transfer to the outside world the three frames acquired by the camera during an experimental run. This arrangement results in a "photons-to-bits" system on a chip. The hybrid chips can be butted on two sides, and thus a mosaic of 4 chips can form a (1440 × 1440) 2-megapixel imaging array.

the current system inefficiently converts light from the scintillator image to a digital image, which reduces the image quality. Finally, each of the system's charge-coupled device (CCD) cameras can store only one frame per experimental run, so many CCD cameras or lower resolution "framing cameras" are required to make a multiframe pRad movie.

To solve these and other problems, we have developed a new camera consisting of two silicon chips bonded together to form a "hybrid chip." The two circuits are a 720 × 720 array of fast silicon photosensors and a complementary metal oxide semiconductor (CMOS) integrated circuit, which can turn the signals from the photosensors on and off to measure the intensity of the incident light in as little as 100 nanoseconds, although typically the camera is operated at an exposure time of 250 to 400 nanoseconds (Figure 2). The CMOS circuit then processes the photosensors' outputs and combines them into a frame; the new camera can capture three frames per experimental run. The photosensor array and all the control-and-processing circuitry are contained in the ~20 × 20 mm^2 hybrid chip. As a result, the new camera is small, consumes only 2 watts of electrical power, needs few external electrical connections, and is highly reliable.

We chose to use advanced, but still "off-the-shelf," CMOS technology to design the large, complex circuit that both shutters the photosensors and processes their outputs, resulting in a "photons-to-bits" chip. CMOS is a mature but still-evolving technology used to produce the sophisticated microprocessors in personal computer

Figure 3. Silicon Photosensor Quantum Efficiency Compared with Scintillator Emission Spectrum
The silicon photosensors produce images with high signal-to-noise ratios because their quantum efficiency (green circles) is high at the scintillator's emission peak (black line). Quantum efficiency measures how efficiently a photodetector converts incident light to electrons. The new camera's quantum efficiency is about 85% at the emission peak (at about 415 nm), and due to the thin antireflective coating shown in Figure 2, little light is reflected at the interface between air and the photosensor's top layer. In contrast, the current CCD imaging system uses a cumbersome two-step process to convert light to electricity (as described in the caption to Figure 1), making it difficult to increase the current system's quantum efficiency much above its current 15%.



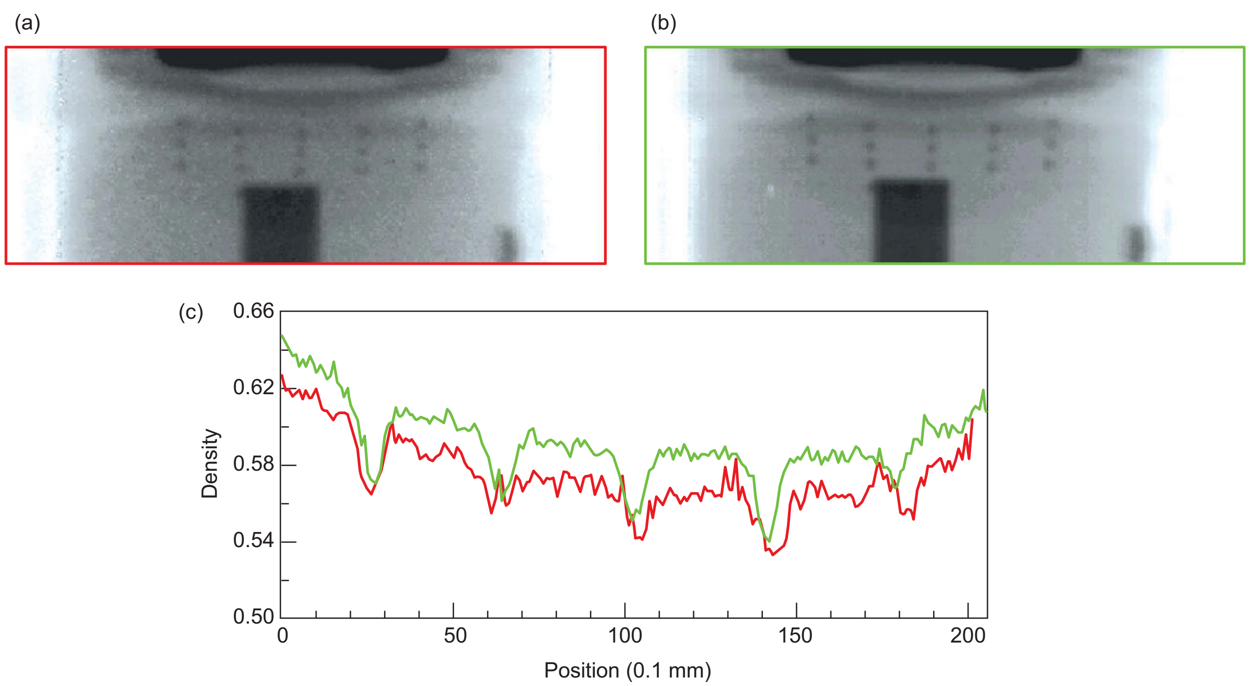


Figure 4. A Comparison of Signal-to-Noise Ratios and Position Resolutions for the Old and New Cameras
The small circles in the proton radiographs shown in (a) and (b) are gold spheres 0.635 mm in diameter. The spheres are sharper in (b), the image produced by the new hybrid CMOS camera, than in (a), the image produced by the old CCD camera because the new camera's silicon photosensors have high quantum efficiency, resulting in high signal-to-noise ratios in the images. (The improvement is even more impressive because the new camera's image contains about half a million pixels, about one-fourth the pixels in the old camera's image.) (c) Line scans of the radiographs through the center spheres quantitatively show the new camera's improved image resolution.

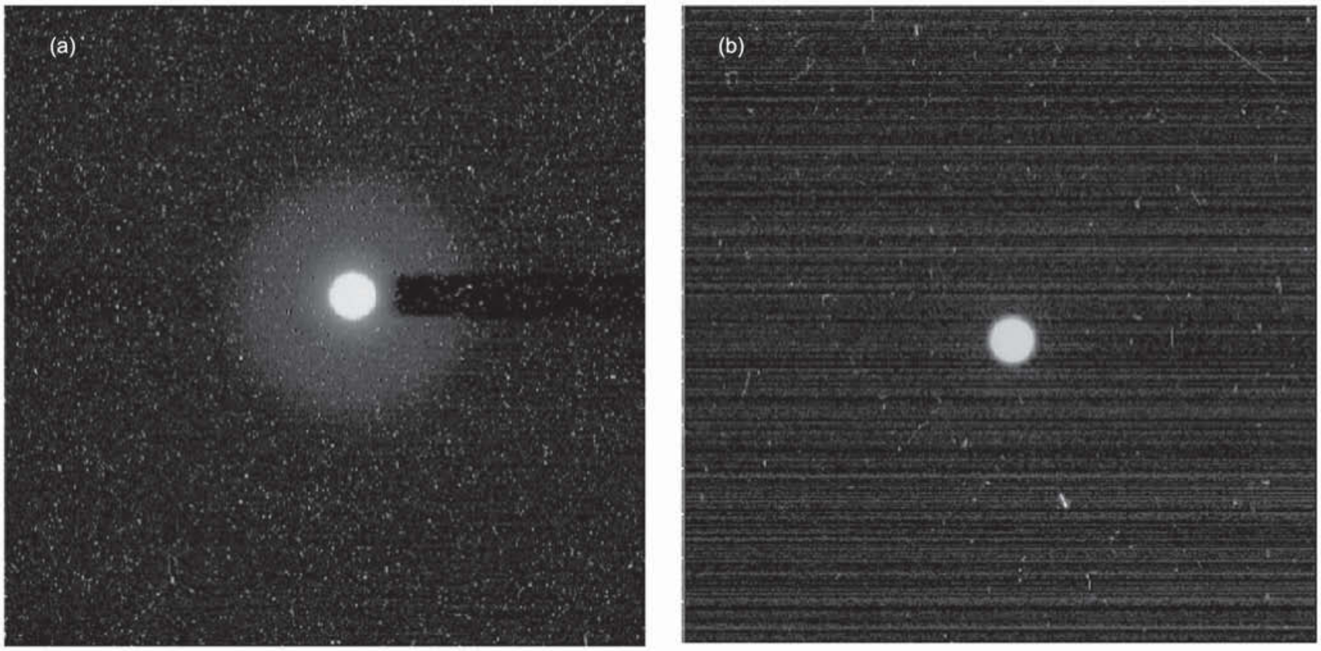


Figure 5. A Comparison of Camera Halos
These images were produced by exposing the old and new cameras for about 400 ns to a scene containing a bright circular spot. The large, bright halo around the spot in the old camera's image (a) was produced by the camera's planar-photodiode shutter. The new camera's image (b) has no halo because this camera is shuttered more directly and efficiently. The tiny white "stars" were produced by stray radiation, to which the new camera is clearly less susceptible. The horizontal lines in the right image are camera noise considered to be negligible because the intensities in these images are proportional to the logarithms of the intensities in the original images. The intensities of these lines are only about 0.05% of the maximum intensity.

and cell phone circuits; a microprocessor typically contains hundreds of millions of transistors. The new camera's CMOS chip contains over 10 million transistors. The hybrid chip containing both the photosensor array and the CMOS circuit was made at the Rockwell Scientific Company.

The 200-millimeter diameter wafers with 48 CMOS chips were fabricated at the United Microelectronics Corp. (UMC) silicon foundry in Taiwan, one of the largest facilities of this type in the world. Rockwell used its CMOS expertise to design the CMOS readout chip and its facilities to fabricate the photosensor arrays and to assemble the hybrid chips with minimal development costs.

The proton radiography team routinely operates the new camera in a burst mode at 2.8 million frames per second but has successfully operated it as high as 4 million frames per second. The shutter control for the new camera is a fast 3-volt pulse, whose width determines the exposure time. This pulse is easy to generate and results in faster shutter times than those possible with the vacuum planar photodiode.

At wavelengths near the scintillator's light-emission peak, the new camera's quantum efficiency is 4 or 5 times that of our current camera system (Figure 3). Higher quantum efficiency means greater sensitivity to the scintillator light and therefore a higher "signal-to-noise" ratio in the images, allowing finer details to be seen (Figure 4). Although we could achieve higher image quality with our current camera system by increasing the proton beam intensity by the same factor of 4 or 5, that would require upgrading the large, expensive accelerator that generates the 800-million-electron-volt protons that produce the radiographs.

Moreover, as shown in Figure 5, unlike the old camera, the new camera produces no "halo." The photos in Figure 5 also show the responses of the two cameras to stray radiation from the proton beam, which appears as tiny white spots (called "stars"). The lack of halos and the reduced response to stray radiation also improve the new camera's image quality.

The hybrid camera is also less susceptible to permanent damage from stray radiation. We typically replace each CCD camera in our current camera system every two to three years because of radiation dam-

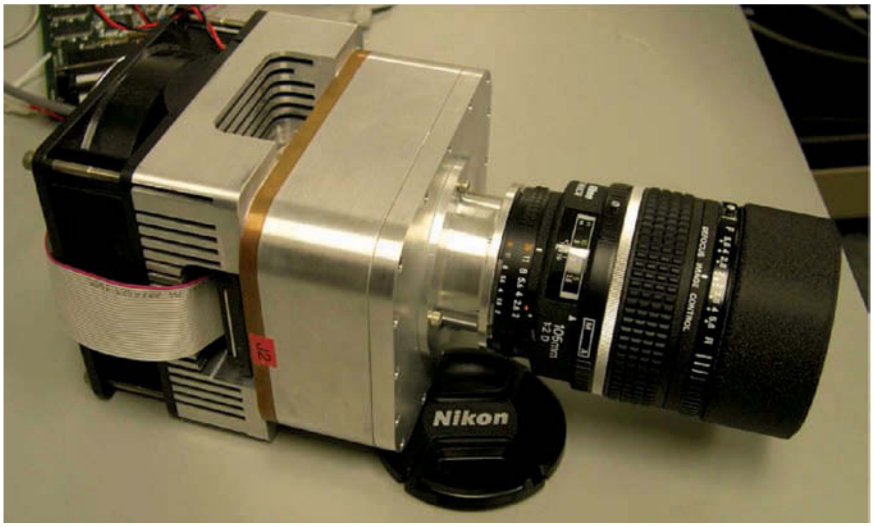


Figure 6. The First Prototype of Our New Camera
The hybrid camera on a chip is mounted inside the solid-aluminum "camera body." The red-striped gray cable shown is one of two such cables that provide all connections necessary to operate the camera, which consumes only 2 W of electrical power. The slotted-aluminum piece and black fan mounted on it comprise a cooling system that reduces thermal noise in the images (the hybrid imager is operated at 0ºC). Five more prototypes are being made. In addition, hybrid-chip cameras that will provide images with 1440 × 1440 pixels could be developed by either building a mosaic of four hybrid chips or more efficiently by using the same basic design but "stitching" together four CMOS chips at the foundry to increase the pixel count by a factor of 4. (Stitching is a nonstandard CMOS process. That is why we did not use it for the first prototype.)

age. At about $100,000 per single CCD-based camera system, the savings realized by using the new imagers will be considerable.

Finally, as mentioned above, the new camera stores three frames, but it has the potential, as CMOS technology advances, to store at least 10 frames in the near term and possibly hundreds of frames eventually. Thus, fewer of the new cameras will be required to capture the same total number of frames—reducing the cameras' total cost, the time required to calibrate all of the cameras for each experiment, and the real estate of the cameras in the experimental area—where space is at a premium. The reduced space requirement also permits improved radiation shielding for the camera system. A prototype of the new camera is shown in Figure 6.

Although the new camera was designed specifically to make pRad movies, it can also be used to make visible-light and near-infrared movies of other fast dynamic phenomena, such as projectiles penetrating armor. It could also be used for multiframe flash x-ray imaging applications, possibly at the Los Alamos DARHT facility. The current 720 × 720 pixel array exceeds the array size and dynamic range of other visible-light, directly shuttered silicon-array cameras. Similar CMOS technology can also be used to measure much shorter, namely, nanosecond-scale changes, in light intensity for VISAR systems, which measure the velocity of an object's surface by measuring the Doppler shift of light reflected from the surface. Alternatively, it can perform ultrafast shadowgraphy measurements, or diagnostics of other ultrafast transient phenomena such as plasma fusion. In short, we see the new camera as the fast imaging technology of the future. ■

Further Reading

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